

Thermodynamic and thermo-economic analysis and optimization of performance of irreversible four-temperature-level absorption refrigeration



Mohammad H. Ahmadi^{a,*}, Mohammad-Ali Ahmadi^b, Mehdi Mehrpooya^a, Hadi Hosseinzade^c, Michel Feidt^d

^a Department of Renewable Energies, Faculty of New Science and Technologies, University of Tehran, Tehran, Iran

^b Department of Petroleum Engineering, Ahwaz Faculty of Petroleum Engineering, Petroleum University of Technology (PUT), Ahwaz, Iran

^c Faculty of Mechanical Engineering-Energy Division, K.N. Toosi University of Technology, Tehran, Iran

^d Laboratoire d'Energétique et de Mécanique Théorique et Appliquée, ENSEM, 2, avenue de la Forêt de Haye, 60604 54518 Vandoeuvre, France

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ABSTRACT

This paper presents a developed ecological function for absorption refrigerators with four-temperature-level. Moreover, aforementioned absorption refrigerator is optimized by implementing ecological function. With the aim of the first and second laws of thermodynamics, an equivalent system is initially determined. To reach the addressed goal of this research, three objective functions that the coefficient of performance (COP), the ecological function (E) and thermoeconomic criterion (F) have been involved in optimization process simultaneously. Three objective functions are maximized at the same time. Developed multi objective evolutionary approaches (MOEAs) on the basis of NSGA-II method is implemented throughout this work.

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1. Introduction

Nowadays, costs of energy consumption and electricity compared to those of fossil fuels have caused engineers in most countries to consider using absorption refrigerators instead of compression refrigerators. However, fuel costs need to be controlled in some way and consequently; economical studies are carried out constantly on optimization of absorption refrigerators and reducing their economical costs.

A new criterion has been used in the recent years to evaluate the degree of optimality of thermodynamic cycles. The thermoeconomic criterion economically investigates the phenomena. Capital costs and energy costs are considered in these investigations using thermodynamic relationships and working conditions are designed in a way that the operation is economically optimum. Chen and Schouten evaluated the optimal value of coefficient of performance in irreversible absorption refrigerator systems [1]. Next, Chen in 1999 evaluated the optimal value of coefficient of performance for the irreversible 4-heat exchange-surface absorption refrigerator in the maximum specific cooling load [2]. This was followed by other researches with the aim of optimization of absorption

refrigerator processes and other processes similar to those, including thermoeconomic optimization of the reversible sterling heat pump cycle by Tyagi et al. [3]. The largest portion of capital cost of absorption refrigerator pertains to the heat exchangers used in the generator, condenser, evaporator, and the absorber.

From economical point of view, incorporation of absorption refrigerators with the combined power and heat (CHP) systems has high profit. Since the 1970s finite-time thermodynamics have been used for thermal systems analysis. Angulo-Brown was suggested an ecological criterion [4] for optimizing refrigerator system. The aforementioned suggested criterion is illustrated as $\dot{E} = \dot{W} - T_L \dot{\sigma}$ for the finite-time Carnot machines. In which, T_L stands for the temperature of cold reservoir, and σ represents the production of entropy production throughout the system. Yan verified which the ecological index as $\dot{E} = \dot{W} - T_0 \dot{\sigma}$ is more practical [5]. Where, T_0 is the ambient temperature. There are a great number of attentions in the previous works for the optimization of irreversible absorption refrigerators. Bhardway and colleagues optimized absorption refrigerators utilizing finite-time thermodynamics [6,7]. Moreover, Huang and colleagues studied the COP, surface area, and ecological principles for the irreversible absorption with four-temperature-levels [8]. Chen presented models for the optimization of absorption refrigerators [9,10]. Sun and colleagues investigated the optimization of the relationship between

* Corresponding author.

E-mail address: mohammadhosein.ahmadi@gmail.com (M.H. Ahmadi).

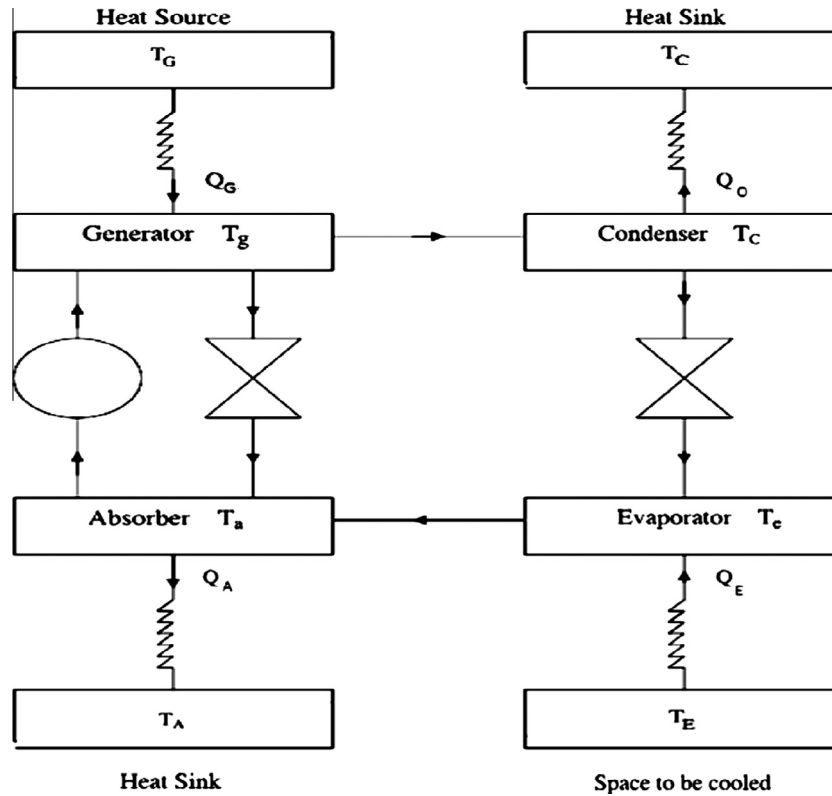


Fig. 1. Generalized four-temperature-absorption refrigerator system [3].

entropy production and heating load of the internal heating heat exchanger [11]. Furthermore, Chen and colleagues presented an approach for the analysis of absorption refrigerator cycles with four-temperature-levels [12]. Chen and Yan optimized the ecological criterion of an irreversible absorption heat exchanger [13].

Two well-known researchers [14,15] optimized the absorption cycles for the ecological criterion for the irreversible Carnot cycles with three-temperature-levels. Fathi et al. presented an approach for solar and irreversible absorption cooling [16]. Furthermore, excluding for the ones specified now, there are numerous optimization of performance investigates for absorption refrigerators [17–20]. Moreover, latest optimization approaches named ‘advanced exergy based analysis approaches’ [21,22] or ‘exergy-entropy relationship’ [23] of the system can be studied for the further researches. Hellmann [24] analyzed the effect of a supplementary restriction, or of an additional operational variable required. Hajtaleb and Feidt, and Vasilescu et al., have also evolved sensitivity analysis to a 4 heat reservoirs refrigerator [25,26]; these two communications were completed [26] by optimization of the COP for a four finite reservoirs reverse cycle irreversible machine (heat pump or refrigerator), and the analogous parametric analysis was accomplished.

Multi-objective optimization is useful way for solving engineering problems at various fields for research [27–29].

Solving the optimization of multi-objective problem requires synchronized satisfaction of different objectives. Thus, evolutionary algorithms (EA) were established and evolved through the 20th century in an effort to solve multi-objective issues at random [30]. A suitable way to a multi-objective quandary is to inquiry an collection of routes, each of them convinces the objectives at a satisfactory degree away being overcome by another route [31]. Multi-objective optimization quandaries generally stand for a feasibly countless group of routes which named frontier of Pareto,

whose assessed vectors show the foremost feasible exchanges throughout the objective function region. Recently, multi-objective optimization of diverse thermodynamic and energy systems were employed in different field of science [32–45].

In our study, in order to maximize the coefficient of performance (COP) and the ecological function (E) and thermoeconomic criterion (F), multi-objective optimization algorithms has been employed. Error analysis was performed to determine accuracy of ultimate results of various decision making methods.

2. Thermodynamic analysis of system

Thermodynamic analyses have been performed for the equipollent system, and earlier equations presented by Refs. [46–53] have been implemented throughout the determinations. The ambient temperature was supposed as 290 K. The scheme of the general absorption refrigerator which under studied here is depicted in Fig. 1.

2.1. Thermodynamic analysis of the generator-absorber assembly (heat engine part)

Thanks to the first law of thermodynamics,

$$\dot{Q}_G - \dot{Q}_A - \dot{W} = 0 \quad (1)$$

In which, $\dot{Q}_A$ (heat output to the absorber heat sink) and $\dot{Q}_G$ (heat input from the generator heat source) can be formulated as following as:

$$\dot{Q}_G = \alpha A_G (T_G - T_g) \quad (2)$$

$$\dot{Q}_A = \beta A_A (T_a - T_A) \quad (3)$$

Thanks to the second law of thermodynamics [13–15,46–53],

$$\frac{\dot{Q}_G}{T_g} - \frac{\dot{Q}_A}{T_a} \leq 0 \quad (4)$$

$$\frac{\dot{Q}_A}{T_a} = I_H \frac{\dot{Q}_G}{T_g}$$

In which, I_H represents the parameter of internal irreversibility for generator-absorber assembly. $I_H = 1$ should be consider for the reversible cycles, and $I_H > 1$ for the irreversible cycles. Heat transfer surface area ratio (a_H), total heat transfer surface area ($A_{T,H}$) and Working fluid temperature ratio (x_H) for the absorber-generator assembly can be defined as following [53]:

$$x_H = \frac{T_a}{T_g} \quad (5)$$

$$a_H = \frac{A_A}{A_G} \quad (6)$$

$$A_{T,H} = A_G + A_A \quad (7)$$

T_g , T_a , and $\dot{Q}_G$ can be formulated by employing Eqs. (2)–(7) as following as [53]:

$$T_g = \frac{I_H \alpha T_G x_H + a_H \beta T_A}{x_H (a_H \beta + I_H \alpha)} \quad (8)$$

$$T_a = \frac{I_H \alpha T_G x_H + a_H \beta T_A}{(a_H \beta + I_H \alpha)} \quad (9)$$

$$\dot{Q}_G = \frac{\alpha A_{T,H}}{1 + a_H} \left(\frac{a_H \beta (T_G x_H - T_A)}{x_H (a_H \beta + I_H \alpha)} \right) \quad (10)$$

2.2. Thermodynamic analysis of the evaporator–condenser assembly (refrigerator part)

Based on the concept of the first law of thermodynamics,

$$\dot{Q}_C - \dot{Q}_E - \dot{W} = 0 \quad (11)$$

Here, $\dot{Q}_E$ (heat input to the evaporator) and $\dot{Q}_C$ (heat rejection from the condenser) are

$$\dot{Q}_C = \mu A_C (T_c - T_C) \quad (12)$$

$$\dot{Q}_E = \theta A_E (T_E - T_e) \quad (13)$$

According to the second law of thermodynamics [13,15,46–53],

$$\frac{\dot{Q}_C}{T_c} - \frac{\dot{Q}_E}{T_e} \leq 0 \quad (14)$$

$$\frac{\dot{Q}_C}{T_c} = I_R \frac{\dot{Q}_E}{T_e}$$

In which, I_R represents the parameter corresponds to internal irreversibility for evaporator–condenser assembly. $I_R = 1$ should be consider for the reversible cycles, and $I_R > 1$ for the irreversible cycles. Total heat transfer surface area ($A_{T,R}$), and x ratio of heat transfer surface areas (a_R), and total heat transfer surface area ($A_{T,R}$) for the evaporator–condenser assembly can be defined as following formulas [53]:

$$x_R = \frac{T_e}{T_c} \quad (15)$$

$$a_R = \frac{A_C}{A_E} \quad (16)$$

$$A_{T,R} = A_C + A_E \quad (17)$$

T_c , T_e , $\dot{Q}_C$ and $\dot{Q}_E$ can be defined using Eqs. (12)–(17):

$$T_c = \frac{\mu T_C x_R a_R + \theta I_R T_E}{x_R (a_R \mu + I_R \theta)} \quad (18)$$

$$T_e = \frac{\mu T_C x_R a_R + \theta I_R T_E}{(a_R \mu + I_R \theta)} \quad (19)$$

$$\dot{Q}_C = \frac{\theta A_{T,R}}{1 + a_R} \left(\frac{I_R a_R \mu (T_E - T_C x_R)}{x_R (a_R \mu + I_R \theta)} \right) \quad (20)$$

$$\dot{Q}_E = \frac{\theta A_{T,R}}{1 + a_R} \left(\frac{a_R \mu (T_E - T_C x_R)}{(a_R \mu + I_R \theta)} \right) \quad (21)$$

The evolved ecological function which includes the magnitudes of maximum energy destruction of the system, maximum power output for the heat engine, and maximum cooling load in the absorption cooling system is defined as following as [46–53]:

$$E = \dot{Q}_E + \dot{Q}_G - \dot{Q}_A - T_o \left(\frac{\dot{Q}_A}{T_A} - \frac{\dot{Q}_G}{T_G} + \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_E}{T_E} \right) \quad (22)$$

The coefficient of performance of the absorption system can be formulated as following as [13,15,49–53,55]:

$$COP = \frac{\dot{Q}_E}{\dot{Q}_G} \quad (23)$$

And the specific cooling load is obtained as follows:

$$r = \frac{\dot{Q}_E}{A} \quad (24)$$

$$A = A_{T,H} + A_{T,R} \quad (24a)$$

Eqs. (23) and (24) are the general relationships for absorption refrigerators with four reversible heat sources. These relationships can be used to obtain thermo-economical optimum performance for this type of absorption refrigerators. According to the studies carried out by Kodali et al. as given in [54], the thermoeconomic criterion for absorption refrigerators with four reversible heat sources is defined as the total price of unit cooling load which includes both capital and energy costs. Therefore, the function which is to be optimized is as follows:

$$f = \frac{\dot{Q}_E}{C_i + C_e} \quad (25)$$

where C_i , C_e are capital and energy costs in the unit of time, respectively. The capital cost of absorption refrigerators is assumed to be proportional to its total heat transfer area:

$$C_i = k_1 A \quad (26)$$

where k_1 is the capital recovery factor, the capital cost for the unit heat transfer area. Energy consumption cost is directly proportional to the rate of heat input:

$$C_e = k_2 \dot{Q}_G \quad (27)$$

where k_2 is the unit cost of energy. By substituting Eqs. (26) and (27) in Eq. (25), we obtain:

$$f = \frac{\dot{Q}_E}{k_1 A + k_2 \dot{Q}_G} = \frac{1}{\frac{k_1}{r} + \frac{k_2}{COP}} \quad (28)$$

By defining $k = \frac{k_1}{k_2}$ as the thermoeconomic parameter having the dimension $\frac{KW}{m^2}$, when the capital cost increases and the cost of energy consumption reduces, the thermoeconomic parameter k goes up.

The ration of the optimal value of the thermoeconomic criterion of absorption refrigerators with four reversible heat sources is obtained as follows:

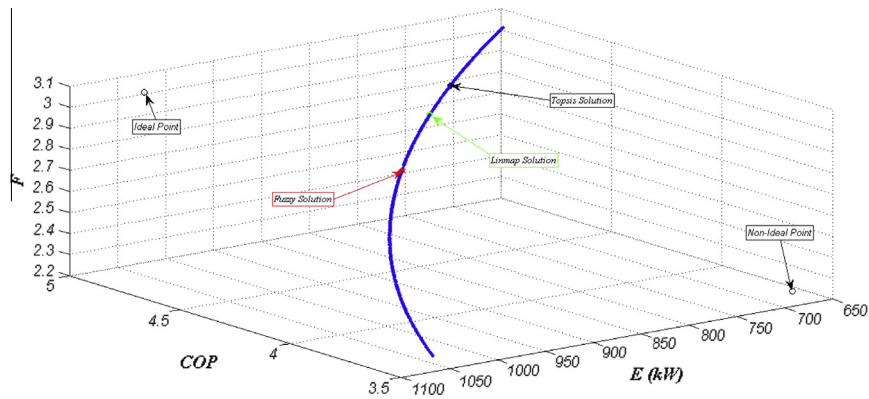


Fig. 2. Pareto frontier (Pareto optimal solutions) using NSGA-II.

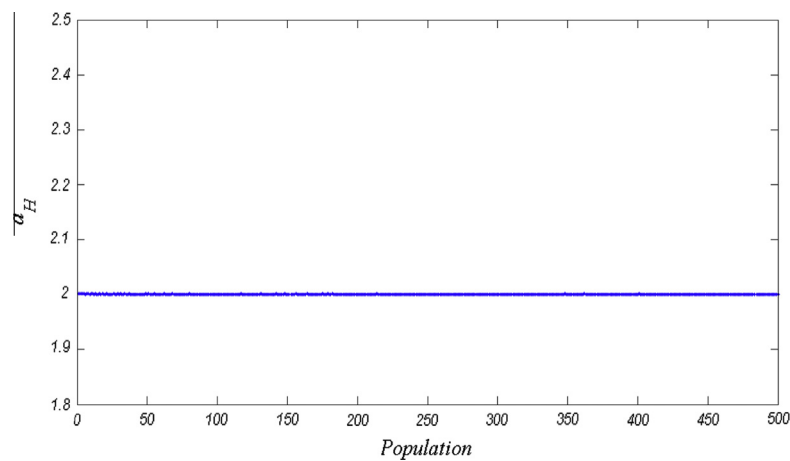


Fig. 3. The distribution of a_H for the optimal points on Pareto front.

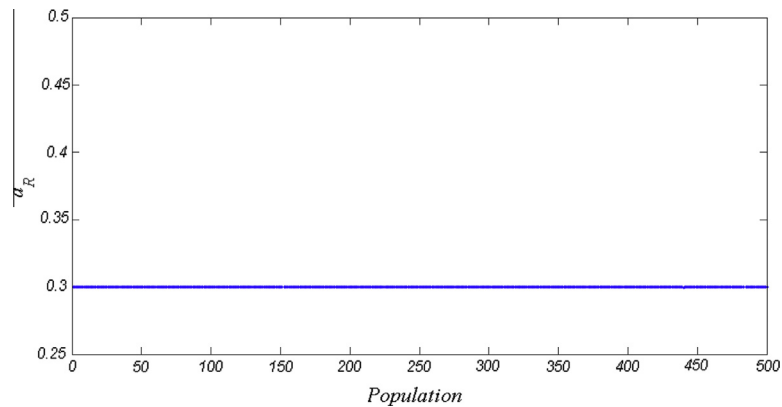


Fig. 4. The distribution of a_R for the optimal points on Pareto front.

$$F = k_2 f = \frac{1}{\frac{k}{r} + \frac{1}{COP}} \quad (29)$$

3. Optimization process

3.1. Evolutionary algorithm: genetic algorithm

Genetic algorithms use a repetitive, random search method to find the best answer and copy it in an easy way principle of biolog-

ical evolution [56]. First parameter in an evolutionary algorithm would be the population of individuals. Individual expresses the values of the decision variables and is a potential answer to the optimization problem [56]. More about genetic algorithm and its process could be finding in references: [56,57].

3.2. Objective functions, decision variables and constraints

The coefficient of performance (COP) and the ecological function (E) and thermoeconomic criterion (F) three objective functions for

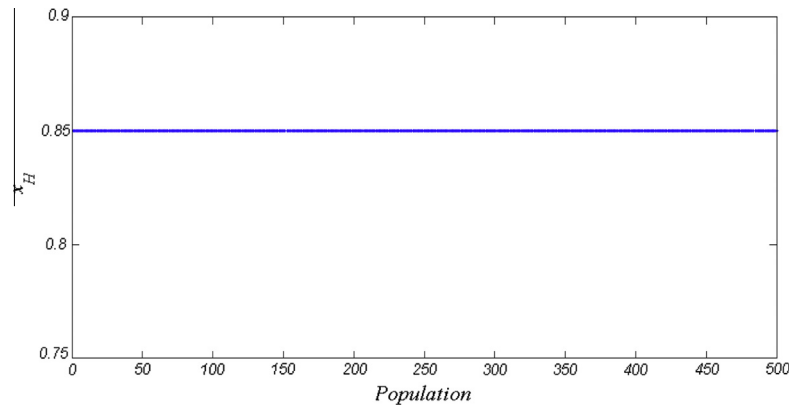


Fig. 5. The distribution of x_H for the optimal points on Pareto front.

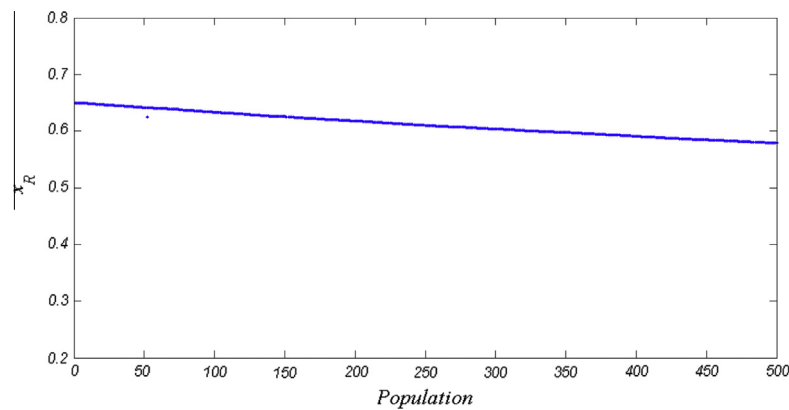


Fig. 6. The distribution of x_R for the optimal points on Pareto front.

Table 1

Decision making of multi-objective optimal solutions.

Decision making method	Decision variables				Objective functions		
	a_H	a_R	x_H	x_R	COP	E (kW)	F
TOPSIS	2	0.3	0.85	0.590	4.33	908.6	2.75
LINMAP	2	0.3	0.85	0.587	4.54	829.4	2.89
Bellman Zadeh	2	0.3	0.85	0.565	4.65	784.2	2.96

this work, which are identified by Eqs. 22, 23 and 29. Four decision variables have been chosen in our study as follows:

- a_H : ratio of heat transfer surface area.
- a_R : ratio of heat transfer surface area.
- x_H : hot working fluid temperature ratio.
- x_R : refrigerant working fluid temperature ratio.

Albeit the decision parameters would be different in the optimization process, each should be in an appropriate interval. By considering following limitations the objective functions was unraveled:

$$2 \leq a_H \leq 2.5 \quad (30)$$

$$0.2 \leq a_R \leq 0.3 \quad (31)$$

$$0.85 \leq x_H \leq 0.95 \quad (32)$$

$$0.55 \leq x_R \leq 0.6 \quad (33)$$

4. Results and discussions

Utilizing multi-objective optimization on the basis of the NSGA-II method, both the coefficient of performance (COP) and the ecological function (E) and thermoeconomic criterion (F) are maximized at the same time. The objective functions in the performed optimization, and the limitations which have been used, are identified by Eqs. 22, 23 and 29 and Eqs. (30)–(33) respectively. The Working fluid temperature ratio (x_H , x_R) and heat transfer surface area ratio (a_H , a_R) are assumed as design parameters throughout the optimization process. Due to agreement with appreciated literatures, following characteristics of the refrigerator system are presumed as below [46–53]:

$$A_E = 150, A_G = 45, I_H = 1.05, I_R = 1.05, T_C = 313 \text{ (K)}, T_E = 288 \text{ (K)}, T_G = 393 \text{ (K)}, T_0 = 290 \text{ (K)}, \alpha = 2.3, \beta = 0.4, \mu = 3.265, \theta = 0.195, T_A = 315 \text{ (K)}.$$

Fig. 2 demonstrates the frontier of optimum Pareto for objective functions E and COP and F , also optimal outcomes of TOPSIS, LINMAP and FUZZY decision making techniques. The span of

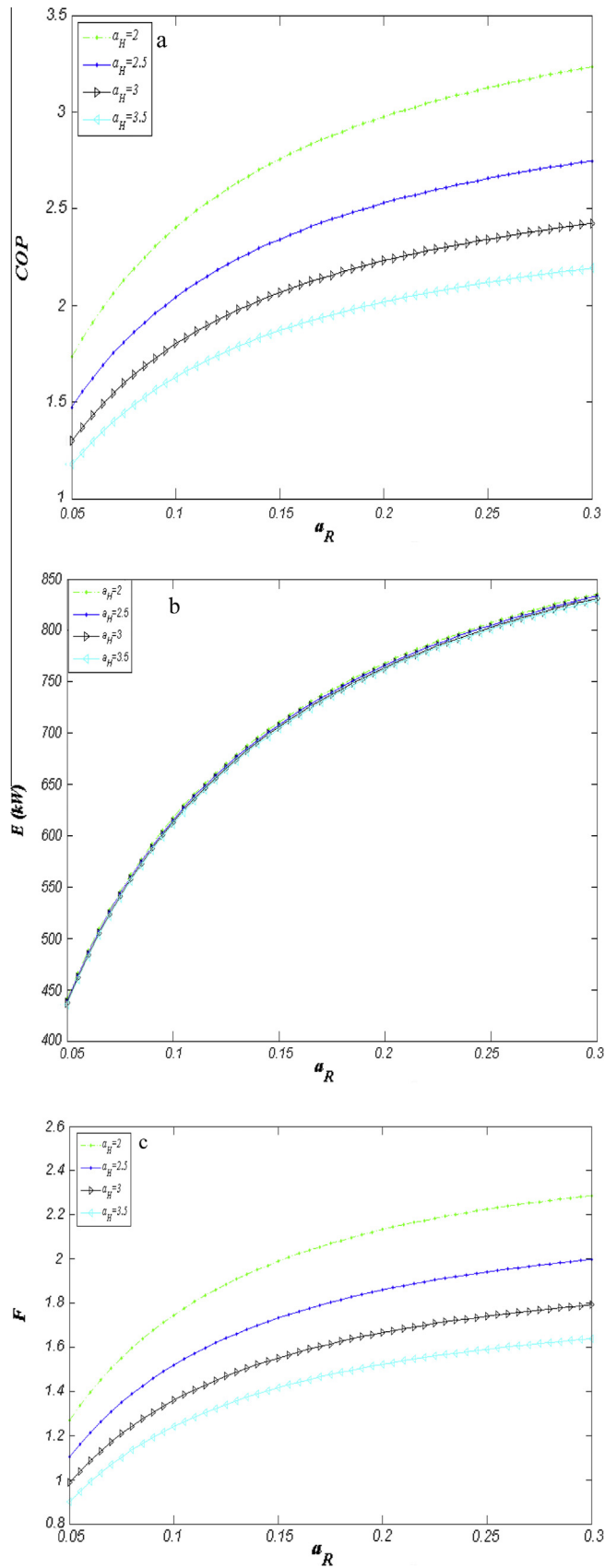


Fig. 7. Effects of the ratio of heat transfer surface area (a_R) and the ratio of heat transfer surface area (a_H) on the (a) coefficient of performance, (b) ecological function, and (c) thermoeconomic criterion.

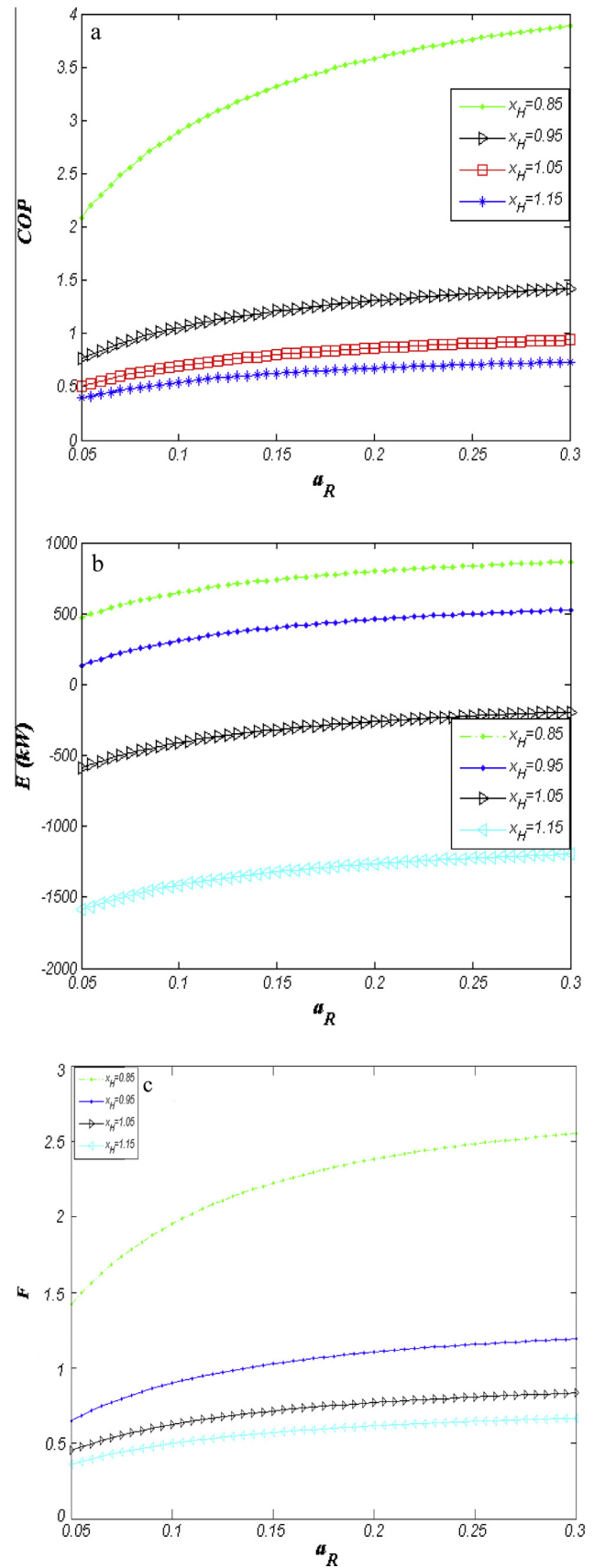


Fig. 8. Effects of the ratio of heat transfer surface area (a_R) and the hot working fluid temperature ratio (x_H) on the (a) coefficient of performance, (b) ecological function, and (c) thermoeconomic criterion.

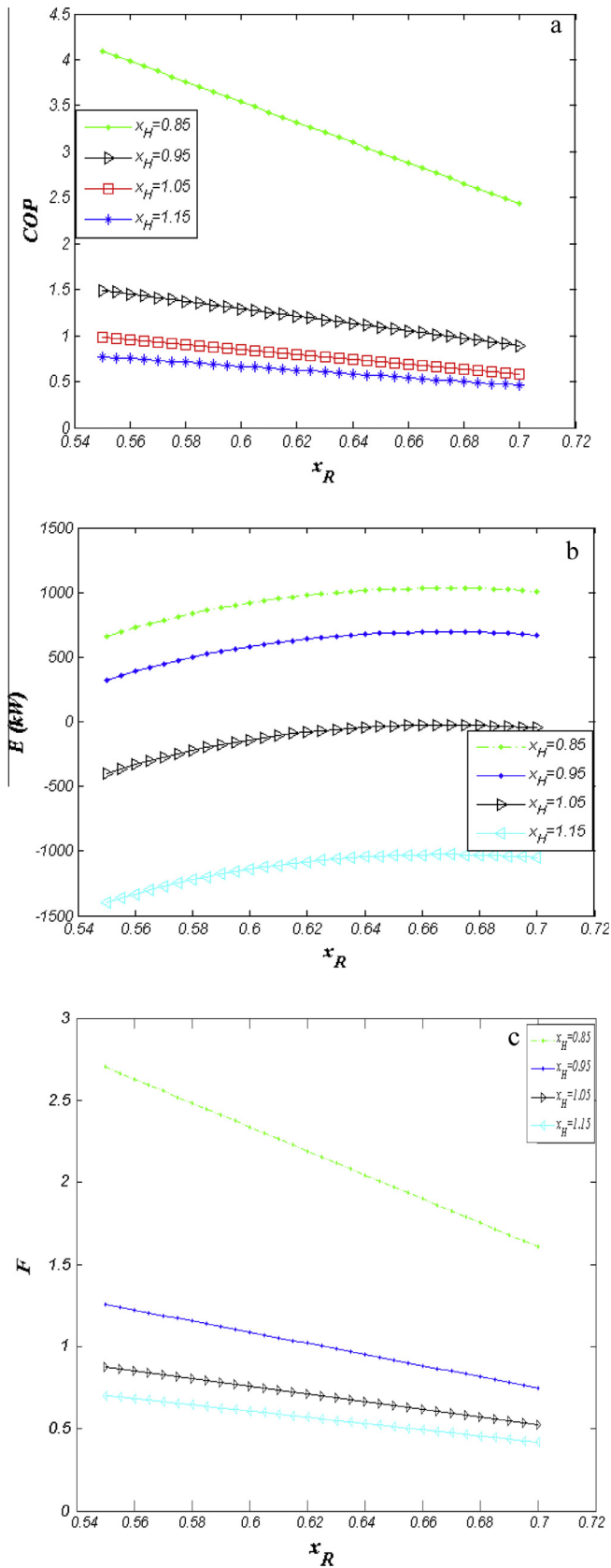


Fig. 9. Effects of the refrigerant working fluid temperature ratio (x_R) and the hot working fluid temperature ratio (x_H) on the (a) coefficient of performance, (b) ecological function, and (c) thermoeconomic criterion.

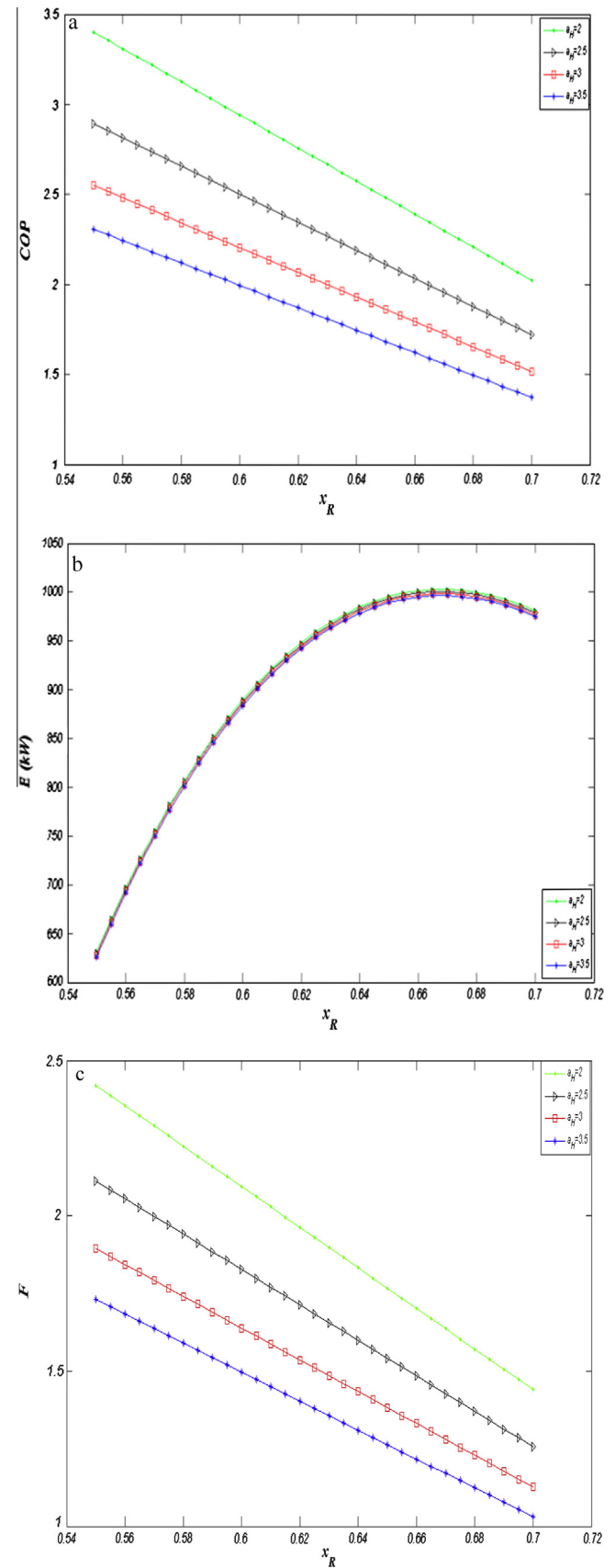


Fig. 10. Effects of the refrigerant working fluid temperature ratio (x_R) and the ratio of heat transfer surface area (a_H) on the (a) coefficient of performance, (b) ecological function, and (c) thermoeconomic criterion.

Table 2

Error analysis based on the mean absolute percent error (MAPE) method.

Error (%)	TOPSIS			LINMAP			Fuzzy		
	COP	E	F	COP	E	F	COP	E	F
Max error	0.4	1.1	0.4	0.9	2.0	0.9	1.7	2.6	1.7
Average error	0.2	0.6	0.2	0.2	0.5	0.2	0.7	1.1	0.7

variations for optimum outcomes of E is from 682.6 to 1057 (kW), and from 3.543 to 4.848 for COP and F is from 2.254 to 3.085.

Figs. 3–6 depict the variation of different magnitudes of decision parameters throughout their accepted span for the optimum design points on the front of Pareto. The variation of the a_H variable is illustrated in Fig. 3.

In Fig. 4 the blue line, shows the greatest magnitude of a_R which is equal to 0.3. Fig. 5 shows that, the variation of different magnitudes of x_H for the optimum design points on the front of Pareto is equal to 0.85. The variation of x_R for the optimum points on the front Pareto is depicted in Fig. 6.

Table 1 shows the optimum outcomes gained for objective functions and decision variables employing Fuzzy Bellman-Zadeh, TOPSIS and LINMAP techniques.

4.1. Sensitivity analysis

From Fig. 7 it can be seen that, the coefficient of performance and ecological function and thermoeconomic criterion increase considerably with increasing of the ratio of heat transfer surface area (a_R) at various values of the ratio of heat transfer surface area (a_H).

In Fig. 8 different system parameters against the ratio of heat transfer surface area (a_R) in the different hot working fluid temperature ratio (x_H) are plotted. And in these figures by increasing the ratio of heat transfer surface area (a_R), the coefficient of performance and ecological function and thermoeconomic criterion will be raised.

In Fig. 9 different system parameters against the refrigerant working fluid temperature ratio (x_R) in the different hot working fluid temperature ratio (x_H) are shown. As can be seen, with increasing the refrigerant working fluid temperature ratio, the coefficient of performance and thermoeconomic criterion decrease and ecological function will be raised.

In Fig. 10 different system parameters against the refrigerant working fluid temperature ratio (x_R) in the ratio of heat transfer surface area (a_H) are shown. As can be seen, with increasing the refrigerant working fluid temperature ratio (x_R), the coefficient of performance and thermoeconomic criterion decrease and ecological function will be raised.

Finally, to determine deviation of the employed methods, error analysis is used. Error analysis is performed according to average absolute relative deviation (AARD) and maximum absolute relative deviation (MARD) of the outcomes obtained from each decision making methods. It should be noted that, error analysis is applied on the final solutions which gained after 30 runs of aforementioned decision making methods. Table 2 summarized outcomes of error analysis for each decision making approach.

5. Conclusions

With the aim of evolved ecological function, the optimization of irreversible absorption refrigerator with four-temperature-levels has been carried out. A balance between entropy production and the load supplied to the system and cooling load has been estab-

lished. The effects of x_H , a_R , x_R , and a_H factors and temperature of operation fluids on the aforementioned system are analyzed.

The ecological function (E), the coefficient of performance (COP) and thermoeconomic criterion (F) are simultaneously assumed for multi-objective optimization, in order to determination by thermodynamic analysis. The ratio of working fluid temperatures (x_H , x_R) and ratio of heat transfer surface areas (a_H , a_R) have been presumed as design variables. The multi objective evolutionary algorithm on the basis of the NSGA-II method has been utilized and the frontier of optimum Pareto throughout the objectives space, was specified. To specify an ultimate solution from the results gained by multi-objective optimization process, three well-known decision making techniques have been implemented and final outcomes are compared on the basis of error analysis.

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